Mitteilung

Projektgruppe/Fachkreis: Technische Strömungen

On the Coverage of Dynamic Processes in Highly Separated Flows Using the Lattice Boltzmann Method

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Ground vehicles are exposed to a vast variety of unsteady aerodynamic phenomena such as gusts. This is why the effect of gusts has been the focus of many studies, e.g. on cars in full scale (Schroeck et al., 2011), trains in full scale (Baker et al., 2004) as well as on simplified car models in wind tunnels (Ferrand, 2014). In order to gain better insight into the flow dynamics, Hemida and Krajnović (2010) investigated the effect of cross winds on a generic train with different nose shapes using large-eddy simulations. Another unsteady effect that has recently gained interest is the multi-stability of the wake behind cars. In this context, Cadot et al. (2016) detected bi-stability in the lift forces acting on full-scale cars during wind tunnel testing. This bi-stability was further investigated in wind tunnel testing on simplified car models by Grandemange et al. (2013) and Pavia et al. (2018).

Due to the highly transient behaviour of the flow, the existing numerical methods require revision concerning their capability of coping with the flow dynamics. For such investigations, the flow around a sphere is usually chosen as a setup, as it has been in the focus of aerodynamic research since the very beginning (Prandtl, 1914) and, thus, is the subject of many studies described in the literature. However, the flow around a sphere is an example of a fully separated flow, whose prediction poses a challenge to numerical investigations such as the DES study of Constantinescu and Squires (2004). The highly instationary dynamics in the wake of such a flow are described by hot-wire measurements (Achenbach, 1972) as well as by flow visualisation (Chrust et al., 2013). The latter clearly shows the development of hairpin vortices and the loss of planar symmetry.

In order to study the force answer of both the influence of incoming sinusoidal, gust-like flow patterns and wake-induced instabilities, Müller et al. (2020) introduced a test setup consisting of a sphere mounted on an internal six-component balance attached to a cross-stream rod (CSR). This setup also included a gust generator equipped with four wings with motor-driven carbon fibre flaps. This experiment provides information on the dynamical behaviour of a highly separated flow over a sphere at a CSR and therefore enhances existing comparisons between numerical and experimental investigations. The present study is intended to evaluate to what extent the dynamics of this flow can be represented by a numerical simulation.

Thus, in accordance with the literature and the above-described wind tunnel tests with a sphere mounted on the CSR, numerical simulations are performed, solving the Lattice Boltzmann equation (LBE). To capture the dynamics of the flow at Reynolds numbers as high as 3×10^5, the Lattice Boltzmann method is chosen to solve the governing equations via 3DS SIMULIA PowerFLOW®. In contrast to traditional numerical methods in fluid mechanics not the Navier-Stokes but the Lattice Boltzmann equation (LBE) is solved in PowerFLOW®. The LBE describes the dynamics of a particle velocity distribution function on a mesoscopic scale. Macroscopic quantities are then deducted via integration of mesoscopic variables. The discrete LBE reads

$$f_i(\mathbf{x} + \mathbf{e}_i \Delta x, t + \Delta t) = f_i(\mathbf{x}, t) + \Omega_i(f(\mathbf{x}, t)), \quad i = 0, 1, \dots, M, \tag{1}$$

where $\mathbf{x}$ is the location in space, $\mathbf{t}$ is the location in time, f_i is the particle velocity distribution function along the ith direction and Ω_i is the collision operator representing the rate of change of f_i due to collision (Chen and Doolen, 1998). Moreover, the collision term is approximated by the Bhatnagar, Gross, and Krook (BGK) model using a linear relaxation (Bhatnagar et al., 1954).

Figure 1 (left) shows a snapshot of the first results of the numerical investigation at Re = 3×10^5. On the leeward side of the sphere with the CSR, the velocity magnitude is depicted as pseudo-colour plot, whereas streamlines are represented in white. Next to the plot is an oil-film photograph reflecting the shear stresses on the sphere's surface. Two counter-rotating vortices can be identified in addition to a region connected to the separation — and consequently recirculation — bubble. Qualitatively, the shape of the pseudo-colour faces matches the shape of the oil film. Note that the plot from the simulation is a snapshot, whereas oil-film visualisations have an averaging character. On the right side in figure 1, hairpin vortex shedding at Re = 280 performed by Chrust et al. (2013) is shown for comparison. Despite the drastically different Reynolds number and test setup, a pair of counter-rotating vortices similar to the one detected with the oil film is observed. The similarity between first numerical results and the experiment and the agreement with the descriptions in the literature appear to be promising, but further investigations need to be performed to

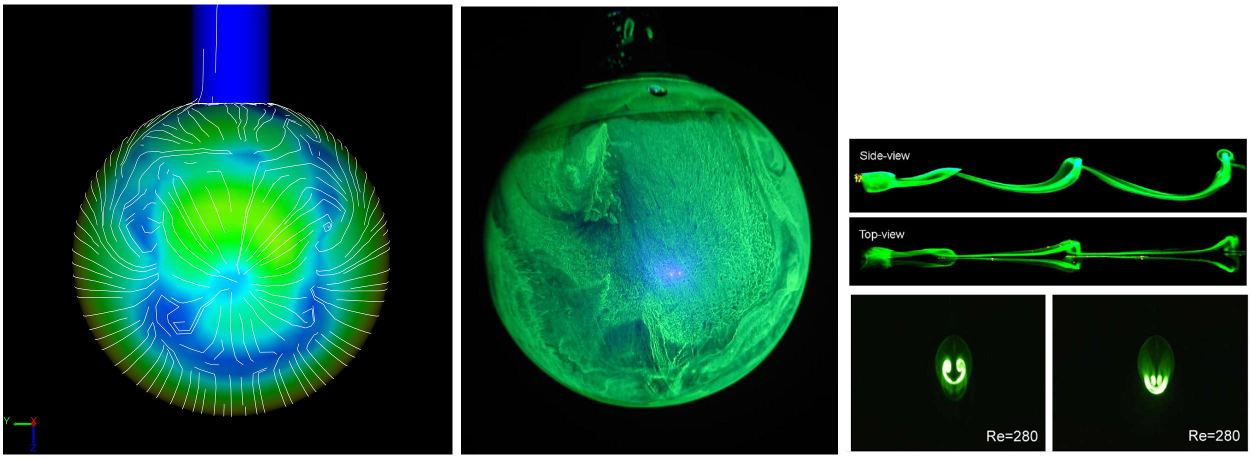

Figure 1: Left: Snapshot of the simulation at Re = 3×10^5 showing white streamlines and velocity as pseudo-colour plot. Middle: Oil-film visualisation of the leeward side of a sphere at CSR at Re = 3×10^5. Right: Wake flow visualisation of Chrust et al. (2013) at Re = 280.

study which flow dynamics and instabilities can be covered by the present numerical method in further detail.

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